Economic Factors in the Introduction of Aircraft Emissions Reduction Technology

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1. EPA's Request and Policy Context

- NASA-EPA MOA to cooperate & consult in aeronautics R&T.

- EPA Director of Mobile Sources requested NASA report to help EPA understand economic factors in introduction of aircraft emissions reduction technology and role the competitive marketplace plays in CO_2 and NO_x emissions reduction.

- Context: International Civil Aviation Organization (ICAO) committed to provide United Nations Framework Committee on Global Climate Change a comprehensive policy options report for reducing civil aircraft emissions under Kyoto Accord.
  - Impacts NO_x & CO_2 emissions in all phases of flight.

- ICAO Council on Aviation Environmental Protection (CAEP) to complete draft report this fall (2000). Then six-month economic analysis and ICAO/ OMB review for decision at ICAO General Assembly Sep-Oct 2001 and transmission to UN.

- NASA's points of contact are delegates to CAEP Technology Options and Market-Based Options working groups from EPA Offices of Mobile Sources (NO_x) and Stratospheric Protection (CO_2), and Federal Aviation Administration (flight safety).

2. Questions from CAEP delegates

- Technology Options working group (re: tighter NOx regulations)
  - *Are regulations the only driver for NOx emissions reductions?*
  - *Any competitive advantages from NOx reduction like reduced fuel burn for CO2?*
  - *What economic factors enter industry decisions on whether to introduce NOx reduction technology? What parameters enter a decision that emissions technology is technically feasible but not economically viable?*

- Market-Based Options working group (re: valuation of fuel and en route levies, emissions trading regimes, and voluntary programs):
  - *How do airlines decide whether to buy a more fuel-efficient aircraft that may cost more ? What level of operating cost reduction justifies what capital cost ?*

- NASA/ EPA study also to be used at EPA-FAA stakeholder meeting on voluntary emissions reduction (3/00). And by FAA to start economic analysis.

- New request for FAA collaboration for their insight into industry tech development progress re: safety-related tech readiness (timing) of next-generation low NOx engines.

3. Impact of NOx Emissions Regulations

NOx emissions regulations apply to engine models certificated after 1986; all the engines in US 1997 fleet were first introduced in the 1960’s, 1970’s, or early 1980’s.

First and second (or current) round of NOx emissions regulations eliminated new production of the engine models first introduced in the 1960’s and 1970’s.
NOx regulations will tighten 16 % after 2003 for newly certificated engines. This will eliminate new production of the engine models first introduced in the 1980’s.

- Replaced by new engines ($ 250 M - $ 2.5 B devt cost, up to 20 yrs to pay back). New engines were Rolls-Royce BR700 (1996-8) & Trents (1994-2003), Pratt & Whitney JT8D E-Kit (1999) & PW6000 (2001), GE90 (1995) & upgrades to GE CF6 (1991), CFM56 (1996), CF6(1991), Honeywell AS900 (2001).

If NOx regulations were tightened another 10% (hypothetical), it would stress every transport engine line, and force a transition to first or second generation staged combustors.

- Rolls-Royce: staged combustors on BR700 after 2002; higher pressure ratio Trents by 2007.
- Allison: 1st gen staged combustor in the wings, 2nd gen with GE (AST/UEET, IHPTET) to test in 2005 (DOD), then evolve to commercial reliability for AE3007, RJE, & GE CF34.
- GE: evolve 2nd gen lean burn from GE/Allison RJE after 2005. Introduce into new derivatives of CFM56 (2008), CF6, and GE90. First may be GP7000 for Airbus A3XX in 2004.
- Pratt: Introduce PW6000 first gen rich burn (2001) & evolve to high PR for PW2000, PW4000, and maybe PW8000. Second generation in development.

CAEP places high priority on increased NOX stringency & NOx cruise standard.
Rationale is that regulations are only driver for NOx reduction.

4. Fleets and Scenarios: 1998 to 2012

- In 1999, there were 28,932 jet engines on 13,541 commercial transports world-wide, and 39,409 jet engines including regional jets and large business jets in overlapping product lines. North America owned 44 %. US airlines owned $ 68 B of flight equipment (aircraft & engines) in 1998 and leased $ 80 B more.

- Scenario 1: Suppose we had to re-engine the entire world fleet rapidly. It would cost $ 157 B to replace existing engines with newer models at current prices, and take 9.5 years to cycle the planes through 733 existing facilities doubling their standard 20,000 flight hour D-check (a $ 1-2 M aircraft strip and rebuild), with a third of capacity reserved for annual C-checks. Facility-related cost: $ 18-38 B.

- Scenario 2: In the next ten years, airlines will purchase 27,839 new engines worth $ 125 billion. With attrition, world fleet will reach 17,028 transports. Ignore spares & simplify to a twin-engine fleet. Will replace 72% of existing engines, leaves 6,000 pre-1998 engines in service.

- [We use a commercial market intelligence service, Forecast International, for conservative supply-chain oriented ten-year forecasts, with detailed model-by-model technical specs, costs and schedule history (AC, engine, avionics, MRO). So we were able to provide EPA with current inventories, airline buying behavior, and future fleets model-by-model with emissions characteristics].

5. Airline Decisions

Profitability:

Airlines decide whether it would be profitable to replace, upgrade, or acquire aircraft based on net present value of revenue-generation potential, ownership cost, and operating cost over aircraft economic life.

- Boeing & Airbus use the same framework to price & market aircraft, adding modest airline profit. Aircraft price is not about manufacturing cost, except during product launch.
- Competing engine manufacturers cannot set price, but use the airline revenue-generation, ownership cost, operations cost framework to value engine benefits from airline perspective

Ability to take on debt :

- Airlines upgrade to the most profitable fleet mix when they can. Often they can't.
- Airlines need 4 % operating margin to service debt, 6 % margin to upgrade fleets.

- Even major airlines often have negative operating margins due to business cycles and fuel price. Bankruptcy is common. Weak airlines are able to obtain capital because US code allows repossession of aircraft from a bankrupt carriers.

[Funded Gellman Research Associates for a cost of capital study including business cycles].

6. Economic Worth to the Airlines:

- Revenue-Generation Potential: yield (cents/RPM), productivity (RPM/day)
  - Airlines can't maintain premium yield; seats are a commodity with declining value.
  - Airlines do compete on productivity. Their marketing, routing, and aircraft technology determines seat capacity, load factor, utilization (hrs/day), and speed.
- Ownership Cost: depreciation, interest, insurance
  - Tax shields (for accelerated depreciation & interest) only benefit airlines with profit.
  - Leasing firms arbitrage the uncertain profitability of business cycle & fuel price.
  - 40-50% of aircraft are purchased with cash flow or loans, 30-40% under long-term (20 yr lease), 20-25% under short-term (5 yr) lease. Rentals are an operating cost.
- Operating Cost: fuel burn, engine maintenance, emissions fees
  - Incentive for CO_2 reduction = reduced fuel burn.
  - Incentive for NOx reduction = maintenance cost reduction for in-service engines.
  - Disincentive for NOx reduction = maintenance cost increase for newer staged

7. Older engines: maintenance cost reduction and fuel nozzles

Two thirds of US fleet (7,100 engines of over 10,000) are models which have been phased out of production, and replaced by more competitive models. Half of the US fleet and a third of the world fleet are Pratt & Whitney JT8D's first introduced in 1963.

Service life is 16 to 25 years with first owner, shorter with the stronger airlines. Second and third tier airlines buy used engines to serve another 5 years. Cargo lines buy older aircraft at $ 10 M with a few months wait, rather than $ 150 M with 3 years wait. Typically re-engine for better fuel burn.

Older engines are not subject to emissions regulations. However the JT8D combustor can be retrofitted to cut NOx 25% (to 77% of current ceiling) for under $ 150 K per engine.

Fuel nozzles are a major culprit for NOx emissions from older engines. Early fuel nozzles coked, clogged, smoked, and leaked raw fuel; service life was a few hundred hours; NOx performance fell in the first year of service. The nozzle tip eroded. Clogged passages changed flow patterns creating hot spots. Poor exit temperature profiles (pattern factors) cut turbine life. For some manufacturers, the fuel nozzles (12-30 per engine) were the most maintenance-intensive item on the engine.

Fuel nozzles pace the maintenance interval (A-checks). Each manufacturer has maintenance & reliability upgrades to reduce direct operating cost by upgrading the fuel nozzle to triple or quadruple the service interval to match the increased utilization of today's transport and regional airline routings, and shared network jets. Longer service intervals increase the probability of low NOx in service. Potential for voluntary NOx reduction.

Similar fuel injector problems on new generations of staged combustors. When an engine idles at altitude, fuel is cold sludge, which can coke and clog the fine passageways used in current designs.

8. NOx reduction during design of derivatives for higher thrust or better fuel burn

- NOx reduction means combustor redesign. Combustor is only 2-4% of engine weight and cost. Last sub-component designed in the traditional hierarchy.

- When an engine is redesigned for greater thrust or lower fuel burn, usually have to redesign the combustor for change in temperature (liner materials, cooling schemes) and airflows (primary combustion air, secondary mixing flows, combustor cooling air, and dilution air for cool-down ahead of the turbines).

- Manufacturers take the opportunity to insert their best-proven low Nox technology. Tech diffusion through the product line. Newest technology is being tested in the active business jet/regional jet engine markets (lower cost testbeds).

- Combustors were hard to design, so they were left alone. But when a designer has done a 3D aerodynamic redesign of the rotating machinery and still needs thrust or SFC, it's a place to look. That means better modeling of turbulent fuel-air flows and combustion processes. Lot of variation in fuel-injectors, fuel-air mixers, and air diffusers esp. swirling, vortex flows for rapid mixing.

9. First generation staged combustors

Lower NOx requires richer or leaner fuel-air ratio. Both reduce combustor stability. In the face of sudden change (e.g. sudden deceleration), flame is likely to blow out. Engine windmills. FAA requires guaranteed relight.

Altitude relight is difficult in lean mixtures, so fuel-rich pilot stage added. Also wanted separate stage for idle for low ground emissions (engines are inefficient at idle because they were designed for take-off & climb). Pilot & idle stage were combined.

Maintenance & reliability problems at idle because fuel was cold sludge moving at a trickle. Hard to push it; hard to atomize for burning. Blockage, distorted airflow, and hot spots. Raised the pressure drop to force it.

When main stage was lean, hard to keep burning in the face of transients. Used prevaporization (combustor heat) to warm fuel and premixing to reduce unburned fuel which could auto-ignite downstream. Pre-mixer created problem of flame flashback; transients caused flames to flashback upstream and stabilize in areas not designed for high temperatures.

When main stage was rich, not all the fuel burned; needed a quench stage to complete the burning. Axial staged combustors (rich burn quick quench) were much longer and heavier, adding shaft weight, more liner area, bearing loads. Pratt tabled the design as not economically viable, not because of price, but because of operability issues.

9. First generation combustors, continued

In lean and rich stages esp. with circumferential fuel staging, combustion instabilities reinforced growth of thermoacoustic waves that coupled stress and thermal excursions into the turbines. Exceeded turbine pattern factor margins; increased wear.

In lean or rich stages, unburned fuel created smoke, & risk of autoignition. DOE sees autoignition in cooling air of industrial gas turbines; DOD sees ignition of unburned fuel in the turbines with catastrophic loss of the interstage seal. To get more air to turbines, designs compromised airflow to the combustor liner, and shifted fuel-air ratio increasing blow-out and relight problems.

In lean or rich staged, random auto-ignition occurred upstream, associated with variations in fuel quality.

Dual annular combustors (lean premixed prevaporized) were twice as expensive. Designs were an order of magnitude more complex. Instead of 12 fuel nozzles, lean and rich designs had banks of flame holders. A CFM56 engine cost $ 250 K more for a dual annular combustor to reduce NOx from 60% of current ceiling to 44 %.

Price was not the issue, performance was. The engines had operability problems in service, higher maintenance costs, and significantly worse SFC than expected. The first dual annular combustors were taken off the market and the engine redesigned to correct the SFC. But there has been low demand. Lessons learned resulted in second generation single annular staged combustors.

10. Economic Incentives and Experience in the Industrial Gas Turbine Market

Incentives:

- In the US and Europe, the ground power market faces more stringent NOx emissions with lower penalties for engine shut-down or catastrophic failure.
- Dry low NOx (staged) combustors offer clear economic pay-off in lower maintenance cost & longer service life, compared to steam injection emissions suppression, which introduces hot-wet corrosion & thermal barrier spallation.
- The $ 114 B ten-year IGT market is as large as the $ 61 B heavy jet engine and $ 54 B regional jet engine markets combined with a different business cycle.
- Manufacturers have developed lean, pre-mixed, pre-vaporized combustors for Rolls Trent/RB211, GE CF-6, Pratt JT8D (future PW4000), Allison/Honeywell turboprops.

Problems in Service:

- Pratt & Rolls-Royce do not consider lean combustors certifiable for aviation.
- Non-stoichiometric fuel-air mixtures are more likely to blow-out with load changes. Lean is harder to re-light so rich pilots are used, but fuel must be shifted in seconds to limit unburned fuel. Cooling air flows are removed to prevent auto-ignition of unburned fuel downstream, can cause failure of turbine seals.
- Operability is a problem. Transients couple to thermo-acoustic instabilities that stress downstream turbines. Transients can cause flame flashback into pre-mixer. Fuel irregularities can cause random auto-ignition.

11. Next Generation Technology: Return to single stage

Airlines demand NOx levels 60% of current ceilings (the best emissions level available for new single stage combustors).

Gameplan is to return to single annular combustors. GE uses lean burn; Pratt and Rolls-Royce choose rich burn.

- Eliminate the complexity of a separate stage for idle; use fuel-air management tailored to flight stages.
- Simplify complex passages that could clog at idle.
- Eliminate any delay in altitude relight and avoid unburned fuel release; integrate the pilots into the fuel injector. Improve flame holders and fuel atomizers.
- Avoid flashback; eliminate pre-mixers; use swirl or vortices to mix fuel and air. Benefit: combustor can be a third shorter than conventional.
- Develop modeling capability to predict fuel-air ratio everywhere including unstable behaviour under transients.
- Switch to high T materials and designs in front end, in case flashback occurs.
- Switch to higher T turbine seals, in case there are pattern factor problems.
- Introduce ceramic matrix composite liners for higher T combustor liner, to free cooling air for fuel-air management needs.
- Develop active controls and diagnostics.
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However, there are still operability problems. NOx emissions at take-off/landing and at cruise are design-sensitive. Design is more difficult at high pressure ratio due to higher temperature which increases instabilities and materials problems.

12. Concerns: Operability and Late Surprises

Engine manufacturers have had unpleasant surprises in engine tests, that weren't seen in rig tests. And have had unexpected operability problems in service. It is very costly and risky to discover problems late in development.

Full scale engine tests are needed to ensure operability because transitions are size-dependent. Sector tests miss radial and circumferential profile effects. Need to examine coupling to the turbines and effects of transients generated upstream in the engine. Manufacturers do not have the knowledge to scale up the effects. Designs are being developed first for business and regional jet engines, which have new market opportunities, and can serve as less expensive platforms. Higher pressure ratios introduce additional design trade-offs that also need to be tested.

NASA's HSR and AST engine tests were cancelled. There will probably by IHPTET engine tests in 2005 (a two-year slip), but given the $ 200 M budget cut, possibly only one team of contractors. DOE's ground turbines are also being used as testbeds, although these are lower temperature and have a very different range of operations.

The concern is that in a lean or rich mixture, designer needs to know that the fuel-air ratio is being managed in every corner of the engine, over the full operating profile, and in the face of transients that can be generated by abnormal flight operations or malfunctions of other parts of the engine.

The designer is also using turbulence and vortices to ensure that the engine relights and that any unburned fuel is well-mixed and recirculated so it can't ignite elsewhere. There is a lot of effort in code development, but it is not at the predictive level yet. There will also be messy effects like coking, blockage, combustor erosion, oxidation, fuel imperfections, that need to be kept in bounds.

There is a learning curve, which has not been mastered yet. And the stakes are very large.